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On Q* and the Dynamics of Diffusion Flames

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ABSTRACT

A dimensionless scaling parameter originally derived by Zukoski from analysis of nonreacting turbulent plumes, Q*, has been applied extensively and successfully in the literature to correlate heights of turbulent diffusion flames. However, from new flame height measurements at laboratory temperature and substantially above and below laboratory temperature it appears that this parameter lacks some generality in the flaming region. An alternative scaling parameter derived some time ago specifically for the flaming region seems to account correctly for the observed variations in flame height with ambient temperature.

1. INTRODUCTION

Analysis of turbulent convective flows resulting from fire leads to a combination of variables with the heat release rate from which a dimensionless heat release rate can be defined, typically represented by the symbol Q*. Zukoski[1] first introduced a form of this parameter about twenty years ago in describing the centerline values of temperature rise and velocity in nonreacting turbulent plumes. However, the parameter has also been applied to correlate features of the combustion region, such as flame heights. Here we report experiments to test the capability of the parameter to account for effects on flame height of variations in the environment, specifically the ambient temperature, compared to another dimensionless parameter, N, introduced a number of years ago[2].

2. THE PARAMETER Q*

Zukoski[1] represented the centerline values of temperature rise, ΔT_o, and velocity, u_o, in turbulent nonreacting plumes as follows:

$$\Delta T_o/T_\infty = C_T(Q^*)^{2/3} \qquad (1)$$

$$u_o/(gz)^{1/2} = C_u(Q^*)^{1/3} \qquad (2)$$

Here C_T and C_u are dimensionless coefficients, T_∞ is the ambient temperature, g is the acceleration of gravity, and z is the height above the heat source. The dimensionless parameter Q* is defined:

$$Q^* = Q/[\rho_\infty c_p T_\infty (gz)^{1/2} z^2] \qquad (3)$$

where Q is the heat release rate and c_p is the specific heat at constant pressure.

An alternative Q* was subsequently introduced by Zukoski et al[3] to correlate a large body of flame height data, substituting the fire diameter, D, for the height above the fire source, z, in Eq. (3), i.e.:

$$Q_D^* = Q/[\rho_\infty c_p T_\infty (gD)^{1/2} D^2] \qquad (4)$$

Dimensionless flame heights, measured under normal laboratory conditions, were shown to correlate very well against this parameter. Other authors subsequently adopted the parameter to correlate flame heights, including Cox and Chitty[4], Hasemi[5], and McCaffrey[6] in his comprehensive review of flame height data and correlations. Still, the rationale for its use in these applications must be said to be unclear, illustrated by Zukoski's recent statement[7] that the "appropriate scaling parameters for most of the features of fire plumes have not been established with confidence." However, "some consensus has been reached that a dimensionless heat addition parameter, [Q_D^*], or a dimensional parameter that is proportional to [Q_D^*] such as $Q/D^{5/2}$ can be used as the scaling parameter."

3. THE PARAMETER N

The parameter N evolved from a capability of predicting maximum gas velocities associated with buoyancy-controlled turbulent diffusion flames, which led to a global model for correlating flame-height data[2]. Infinite reaction kinetics was assumed. Further, it was assumed 1)that the flame would extend to a height where the total flux of air entrained at lower levels is just sufficient to complete the combustion reactions (recognizing that much of the air entrained below the flame tip never takes part in the combustion reactions), 2)that the air demand from the surroundings is proportional to the stoichiometric requirements of the pyrolysis gases, and 3)that the total air entrainment rate obeys the relationship established by Ricou and Spalding[8] for the local entrainment rate in jets of different density than the surroundings. Limiting attention to flames where effects of Froude and Reynolds numbers are not important, the following functional relationship for the dimensionless flame height was derived[2,9]:

$$L/D = fn(N) \tag{5}$$

where:

$$N = [c_p T_\infty/(g \rho_\infty^2 (H_c/r)^3)] Q^2/D^5 \tag{6}$$

In Eq. (6), H_c is the heat of combustion per unit mass and r is the stoichiometric mass ratio, air (or other oxidizing atmosphere) to combustible.

Eq. (5) has been found to correlate experimental data on flame height very well over a wide range of fire sizes and combustibles.[2,9,10] The following correlation equation[9] represents the entire range of fires from values N near 10^{-6} to 10^5:

$$L/D = -1.02 + 15.6 N^{1/5} \tag{7}$$

The high limit on N corresponds to the beginning of effects of high discharge momentum at the source. The low limit ($N = 1.20 \times 10^{-6}$) corresponds to $L/D = 0$, near which experiments indicate that the flame cover will break up into flaming and nonflaming areas[10].

It is readily shown that N and Q_D^* are related as follows:

$$N = [c_p T_\infty/(H_c/r)]^3 (Q_D^*)^2 \tag{8}$$

The ratio H_c/r represents the heat liberated per unit mass of air, or other oxidizing atmosphere, entering the combustion reactions; for the standard atmosphere it does not vary appreciably among various combustibles (most fall within the range 2900 to 3200 kJ/kg). Furthermore, the ambient temperature T_∞ normally does not vary appreciably. Hence, N and $(Q_D^*)^2$ can often be considered proportional to each other, leading McCaffrey[6] to recast Eq. (7) into the following form:

$$L/D = -1.02 + 3.7\,(Q_D^*)^{2/5} \tag{9}$$

Clearly, this conversion applies only to normal atmospheric conditions of temperature, pressure and composition.

To test whether Q_D^* or N is a more suitable parameter, we had the opportunity to conduct a few experiments using a simple methane flame, varying the temperature of the environment substantially above and below normal laboratory temperature. In these experiments, Q_D^* remained practically constant because $\rho_\infty T_\infty$ did not vary much (see Eq. (4)), and inconsequential effects on the flame height are expected if Q_D^* is considered a governing parameter. However, N increased and decreased significantly because of the variations in the ratio T_∞/ρ_∞^2 in the expression for N in Eq. (6), and significant effects on flame height are expected if N is considered a governing parameter.

4. EXPERIMENTS

4.1 Approach

A relatively small turbulent methane flame from a 52.5-mm diameter burner, near 2 kW in heat release rate, was burned at laboratory temperature, approximately 45K above laboratory temperature, and approximately 45K below laboratory temperature. Reference experiments were also run for the elevated and reduced temperature cases at laboratory temperature, matching the parameter N of those cases by, respectively, increasing and decreasing the heat release rate.

4.2 Setup

An environmental chamber was available for conducting the experiments, capable of both elevated and reduced temperatures, Figure 1. Interior dimensions were 3.05 m x 1.88 m x 2.39 m high. The chamber was brought to temperature and then all equipment shut down to provide a quiescent space for each experiment. After an experiment, the door to the chamber was opened and the contents washed out with the discharge of a fan blowing from the outside into the bottom of the doorway.

The exit of the methane burner was at an elevation of 1.27 m below the ceiling at location A or location B. Location A in Figure 1 was used for all experiments except those at reduced temperature (and their reference experiments at laboratory temperature), for which a cold draft was found to descend on the burner from the overhead (deactivated) cooling unit, mounted in close proximity to this location. Location B was selected for the reduced temperature cases and their reference experiments at laboratory temperature.

The chamber was equipped with humidity and temperature sensors. For these experiments, thermocouples were specially installed at three levels on a vertical traverse approximately in the center of the room: level with the top of the burner, 1.12 m above the floor; 1.75 m above the floor; and 2.36 m above the floor (0.025 m beneath the ceiling).

The burner, Figure 2, was made from a 265-mm long section of 2-inch steel pipe, with an internal diameter of 52.5 mm. Methane entered through a tube fitting at the bottom of the burner; the available length-to-diameter ratio was sufficient to meet the requirements[11] for a relatively uniform exit flow from the burner. The square-mesh screen above the gas entry was originally installed to support a bed of glass beads for producing a well behaved flame. The beads were not needed but the screen was left in place. After gas flow was stabilized at the beginning of an experiment, the gas was ignited with the aid of a small loop of nichrome wire extending up from the perimeter of the burner opening, energized electrically to bright-yellow color until ignition. Each burn was limited to a duration of 90 seconds to preclude effects of recirculating combustion products.

Flame heights were determined from video records. The camera viewed the flames through a window in the access door to the chamber. Burner location A was directly in view behind the window. To afford a view of the burner at location B, an angled mirror was positioned at location A. A vertical scale was mounted alongside the burner, approximately 0.20 m to one side and in view of the camera.

In addition to chamber temperatures, barometric pressures (p_∞) and relative humidities in the chamber (RH) were recorded.

Table 1 Test Summary

Test	Burner Location	p_∞ (mm Hg)	T_∞ °C	T_∞ °K	RH(%)	Q(kW)	L(mm)	L/D	10^3N	Q_D^*
1	A	768	29.2	302	39	2.14	315	6.00	10.5	3.06
2	A	768	29.2	302	39	2.14	305	5.81	10.5	3.06
3	A	768	28.4	301	40	2.14	315	6.00	10.4	3.06
4	A	768	28.6	302	39	2.14	325	6.19	10.5	3.06
5	A	764	69.3	342	13	2.13	334	6.36	15.7	3.10
6	A	764	74.0	347	11	2.13	325	6.19	16.6	3.10
7	A	764	72.7	346	11	2.13	338	6.44	16.3	3.09
8	A	760	27.5	301	42	2.66	353	6.72	16.4	3.85
9	A	760	27.5	301	42	2.66	338	6.43	16.4	3.85
10	A	760	27.7	301	42	2.66	330	6.29	16.4	3.85
11	B	760	27.0	301	43	1.65	250	4.76	6.33	2.39
12	B	760	27.2	301	43	1.65	251	4.78	6.33	2.39
13	B	760	27.6	301	43	1.65	257	4.90	6.33	2.39
14	B	763	-17.4	256	52	2.13	254	4.84	6.40	3.05
15	B	763	-17.7	255	70	2.13	257	4.90	6.26	3.05
16	B	763	-17.8	255	72	2.13	257	4.90	6.26	3.05

4.3 Results

Table 1 is a list of experimental results. Flame heights, L, were determined from 75 seconds of each video record, after the first 15 seconds of each burn, as the height above which the flame spent 50 percent of the time. This definition of flame height was first introduced by Zukoski et al.[12] Values of the parameter N were calculated using Eq. (6). Values of Q_D^* were calculated using Eq. (4). Heat release rates were calculated from the mass flow rate of methane gas, assuming complete combustion.

Figure 3 shows L/D as a function of N. The circles represent cases at laboratory temperature and the squares cases at elevated and reduced temperatures. The results at the elevated and reduced temperatures agree very well with their laboratory temperature counterparts at approximately the same values of N, confirming the efficacy of the parameter N. The flame height data are positioned slightly higher than the dashed curve, which is the correlation in Eq. (7).

For comparison, L/D is shown as a function of $(Q_D^*)^2$ in Figure 4. Cases at laboratory, elevated, and reduced temperatures at $(Q_D^*)^2$ near 9.5 clearly lack consistency. The dashed curve represents Eq. (9).

5. CONCLUSION

Flame height measurements at laboratory temperature and approximately 45K higher and lower temperatures have supported the use of the parameter N (Eq. (6)) as a scaling parameter. The parameter Q_D^* (Eq. (4)) does not appear to be a suitable scaling parameter for the flaming region. In practice, the distinction is important mainly when atmospheric conditions differ significantly from standard.

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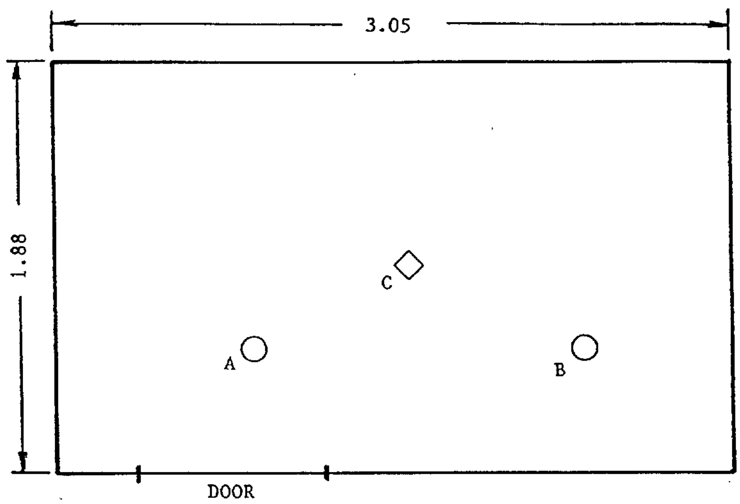

Figure 1 Environmental chamber with locations of burner (A and B) and vertical thermocouple traverse (C) drawn to scale. Interior dimensions in m (chamber height was 2.39 m).

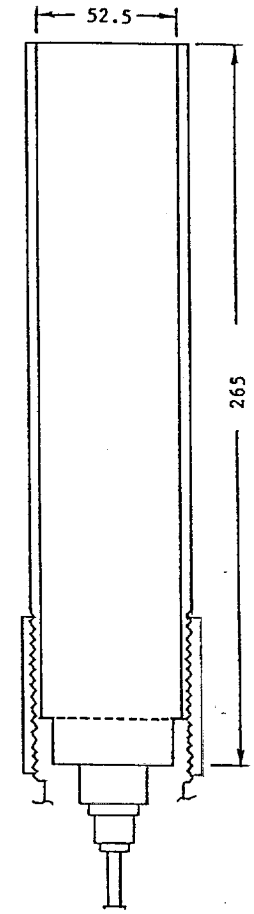

Figure 2 Burner. Methane gas entered at bottom. Dashed horizontal line represents a wire-mesh screen. Dimensions in mm.

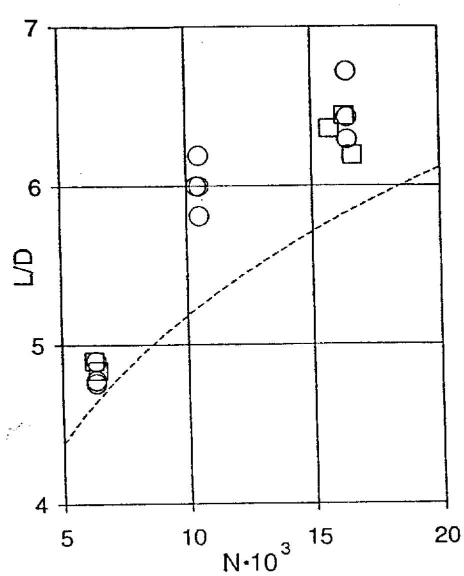

Figure 3 Dimensionless flame height as a function of N. Circular symbols correspond to laboratory temperatures; squares correspond to elevated and reduced temperatures. Dashed curve represents Eq. (7).

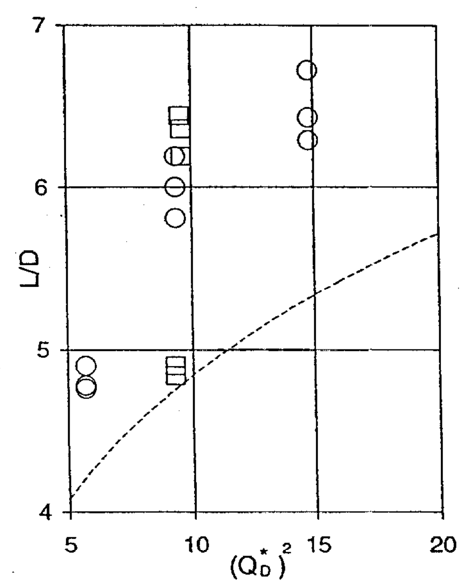

Figure 4 Data in Figure 3 plotted as a function of Q_D^*. Dashed curve represents Eq. (9).

Discussion

Henri Mitler: This morning, Yuji Hasemi pointed out that certain correlations could be improved by taking a mixed set of distances instead of having just D or flame height or whatever. He chose a mixture and tightened up his correlations. I wonder if in the light of what you just described, it might not be worthwhile to revisit the entire thing. Possibly one could reduce the scatter of data still more by very judicious selection of parameters like that.

Gunnar Heskestad: In certain cases in fire dynamics like this one which are very well-defined, we often forget that there are still variations from one case to another. In fluid mechanics, we speak of dynamic similarities. It's required that you have geometric similarity. That's something we have to keep in mind. The second part of my answer is that we should bear that in mind when we look at scatter. It could be departures from geometric similarity.

Edward Zukoski: Is H over R the heating value per kilogram of air?

Gunnar Heskestad: Correct.

Edward Zukoski: Because we've changed the heating value of the fuel by a factor of about 10 by adding nitrogen to it. If I have a constant methane flow and I add 4 moles of nitrogen to the fuel, do you change N?

Gunnar Heskestad: No. You change these the same way.

Edward Zukoski: Okay. So we have done that and it didn't change Q* either.

Gunnar Heskestad: Correct.

Edward Zukoski: We also burned 60 kW fires inside a hood, the flame was up in the hood, and the temperatures went from 30 degrees to 150 degrees as the oxygen mass fraction went down and we saw only about a 5% variation in the flame height.

Gunnar Heskestad: That is a more complicated case and I should say that our experiment is probably a little better controlled so, for now, I will stay with that but it is an interesting test case.

Howard Baum: I am intrigued by your fuel parameter there. If I had something like an oxygenated fuel or anything that was sort of carrying along it's own oxidizer supply to a certain extent, would that change that parameter?

Gunnar Heskestad: No.

James Quintiere: It would seem to me that the term with the temperature and the heat of combustion comes from the fact that you're burning the air that is entrained. And so realizing that H_C over R is constant, the temperature variation seems to confirm that mechanism. Would you see it the same way?

Discussion cont.

Gunnar Heskestad: I think mainly it's the effect of the entrainment rate.

Howard Baum: One other possible test of this, would it be to look at Archie Tewarson's data where he like to change the oxygen concentration.

Gunnar Heskestad: That type of experiment can be done and I have done it. I submitted a paper to the Combustion Symposium which may or may not be accepted but it includes that.

Richard Gann: Isn't H_c /R nominally the oxygen consumption constant that appears in oxygen consumption calculations?

Gunnar Heskestad: Correct.

Richard Gann: Certainly, there is a temperature effect on H_c.

Gunnar Heskestad: In principal.

Richard Gann: It's real because you start with all the species at a higher temperature and therefore, you don't have to warm them quite as much.

Gunnar Heskestad: We have ignored that.

Richard Gann: Anthony Hamins ran some experiments with various fire suppressants in which he varied the temperature of the system and the effectiveness of the suppressants not only changed but the rate of change curves crossed, indicating that there is certainly some change in the suppression chemistry, but entirely possible that there is also some changes in the relative rates of the combustion chemistry as well.

Gunnar Heskestad: It is an interesting comment and I will consider that.

Takashi Kashiwagi: How about changing the amount of gas, not nitrogen/oxygen but helium/oxygen or halogen/oxygen? Might there be a difference between Q* and N?

Gunnar Heskestad: In the paper I mentioned that we changed the oxygen in the environment by introducing nitrogen and we found that would change N, and the flame height should have increased. There was less increase in flame height than we had predicted and there is a discussion in the paper of why that was.

Anthony Hamins: Could you kindly comment on combustion efficiency effects on N?

Gunnar Heskestad: In these experiments the combustion efficiency probably did not vary a great deal because the flame temperatures were very similar in all cases.

Discussion cont.

Anthony Hamins: We've made measurements with propane, acetylene, and a number of other gaseous fuels. Looking at flame height and looking at the correlations, we had problems fitting the correlations to our data for the very sooty fuels. Can you comment on those findings?

Gunnar Heskestad: The combustion efficiency may effect this ratio. That isn't too well-understood, but I think from Huggett's study, probably that was not a factor. In the paper I referred to, we explained the absence of a significant effect of the ambient oxygen concentration in terms of a parameter. We had to leave it for simplicity. The parameter is question is the convective fraction of the total heat release rate. The originally derived parameter was N divided by that fraction.

Takeyoshi Tanaka: I think that the temperature effect on H_c is very small. I am not an expert in this area, but the value M has to do with entrainment. However, I think the mass of the oxygen in the air would not change, so if the temperature of the air goes down, then oxygen increases and I think that probably effects the flame and that is my thinking. Looking at the data you showed us, the difference is not all that great.

Gunnar Heskestad: In answer to that question, I just wish to say that parameter N was derived through a set of assumptions which have been discussed quite thoroughly in the original paper in 1980.